Simulator of track circuit for urban/suburban transit system
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Abstract

The paper presents a Matlab/Simulink based simulator of track circuit for urban/suburban transit system. The sub-systems in this simulator includes the Simulink models for running rails, transmitter, receiver, boosting unit, train occupation and termination circuit. All signals in the track circuit can be observed on the computer screen. The parameters for the running rails were measured in field with real carrier frequencies to account for skin effect and eddy currents. To investigate the impact of train position on the receiver signals, the running rail model for a fixed track length is implemented as two variable length track circuits, separated by the moving train. The impacts of track length, boosting unit, and carrier frequency can also be investigated by means of this simulator. The results from this simulator have been confirmed by comparisons with measurements.

1 Introduction

Track circuit is the basis of modern railway signalling [1-3]. The running rails are normally used for both track circuit and electric traction return purposes, and are in contact with the ground. The power-electronic controlled traction drives and power system can generate in-band harmonic interference currents flowing in the signalling system, resulting in degradation of signal system including unsafe failures [4]. Since 1970, there has been an extensive development of detailed understanding of these effects for modern equipment.
in both DC and AC railway applications [5-7]. A conductive interference coupling model was developed as equivalent circuits, which dissect the complex conductive interference problem into a number of parts for being analysed separately [8]. Both electromagnetic field and circuit simulation models are described in [4], which enable a railway traction system with substations, traction drives, track signalling equipment, track and traction line to be assessed together for low and audio frequency electromagnetic interference [4]. The novel features of these models were the derivation of frequency-dependent track and traction line impedance by the Finite Element Method (FEM) of electromagnetic analysis and the representation of the frequency dependency in circuit simulation by current-dependent voltage sources [4, 9]. The simulation accuracy was further improved by including the crosstalk between adjacent track circuits in the mathematical model, in which the impedance matrix was determined by FEM [10].

This paper utilises Matlab/Simulink for development of the track circuit simulator. It presents detailed Simulink models of the track circuit for urban/suburban transit systems. In addition to high simulation speed, Graphical User Interface (GUI), and powerful Matlab graphing features, this simulator can demonstrate the transient process caused by any parameter variations during the simulation.

Since the type and range of track circuits have changed over years, there are many different types of track circuits in the metropolitan area. In the Brisbane suburban rail network, for example, although AC immune DC track circuits are used near exclusively, there are more than five other types of track circuits are in application or on trial. The simulator presented in this paper is for the CSEE UM71 track circuit utilised in the Gold Coast line of Brisbane suburban area. The major sub-systems of this simulator are transmitter, running rails, train occupation and termination circuit. They are saved in the Simulink library separately. Some of these sub-systems, such as running rails and train occupation, can be directly used in the Matlab/Simulink based simulator for other types of track circuits.

2 Modelling of running rails

2.1 Equivalent circuit

In most applications, the running rails are used as the transmission lines for railway signalling system. An equivalent circuit to simulate the terminal characteristic of the running rails is shown in Fig. 1, where / is the length of the running rails, \( R+sL \) is the rail impedance, \( G+sC \) is the ballast conductance plus rail admittance, and \( R_g \) is the equivalent resistance via ground.
2.2 Transfer functions

The circuit in Fig. 1 can be directly simulated in some simulation software such as SPICE. In the Simulink models, however, one of the easiest way in simulation is to use transfer functions. The transfer functions for the equivalent circuit in Fig. 1 can be worked out as follows:

\[
Z_1(s) = \frac{R_g l^2 \left( \frac{R}{2} + \frac{sL}{2} \right)}{2}, \quad Z_2(s) = \frac{1}{Gl + sC l}
\]

and \( V_1(s) = Z_1(s)I_1(s) + Z_2(s)(I_1(s) - I_2(s)) \)

\[
I_1(s) = \frac{V_1(s) + Z_2(s)I_2(s)}{Z_1(s) + Z_2(s)} = Y(s)V_1(s) + G(s)I_2(s)
\]

\[
V_2(s) = V_1(s) - Z_1(s)I_1(s) - Z_1(s)I_2(s) = V_1(s) - Z_1(s)(I_1(s) + I_2(s))
\]

where details for \( Y(s), G(s) \) and \( Z_1(s) \) can be seen in Fig. 2.

2.3 Simulink model

Based on eq (1), the Simulink model for running rails in the track circuit can be developed, as shown in Fig. 2. The track length \( l \) in this model is replaced with a variable \( x \). It is a sub-system for simulator of the track circuit, which can represent a piece of running rail with a variable track length. For fixed track length analysis, the value for track length \( x \) can be given in the dialog box of this model. When dynamic analysis as locomotive moves along the rail is required, the track length \( x \) can be declared as a global variable in an S-function and calculated from the integral of the locomotive speed over time.
3 Modelling of track circuit

3.1 Transmitter

To provide protection against the various spurious signals from the track, such as AC traction current harmonics, the basic output frequencies of the transmitter in the CSEE track circuit are modulated with a depth of $\Delta f=11$Hz. Thus, the transmitter output consists of two frequencies: $f_0-\Delta f$ and $f_0+\Delta f$. The modulation rate is set by division by 128 of the basic output frequency $f_0$, this is 20.3Hz at $f_0=2600$Hz and 15.6Hz at $f_0=2000$Hz.

Fig. 3(a) shows a Simulink model for the above transmitter, where the output of $S_{\text{control}}$ is a square wave. The Switch SW1 selects either $f_0-\Delta f$ or $f_0+\Delta f$, in accordance to the transmitter modulation rate set in $S_{\text{control}}$. Instead $f_0t$, $\int f_0 \, dt$ is used as the input of the sinusoidal function. This ensures a smooth output voltage when the input frequency switches from one to another.
Fig. 3(b) is the transmitter output waveform at $f_0=2000\text{Hz}$ and $\Delta f=11\text{Hz}$. At $t=0.128s$, the frequency of this waveform changes from 2011Hz to 1899Hz. It can be seen that this transition process is very smooth, as expected.

### 3.2 Boosting Unit

Since the impedance of running rail is inductive, the length of each track circuit can be extended by an RC circuit called “boosting unit”. To be connected in middle of the track circuit, the boosting unit is represented by a two-port circuit. While the input and output voltages of this two port circuit are the same, its input current equals the sum of output current and the capacitive current via the boosting unit, as shown in Fig. 4, where $C_b$ and $R_b$ are capacitance and resistance of the boosting unit respectively.

![Fig. 4. Simulink model for boosting unit](image)

### 3.3 Train occupation

The purpose of the track circuit is to detect the train occupation. When the rail track is occupied by a train, the running rails are shorted together by the wheels. The wheel sets can also be modelled as a two port circuit, using the wheel contact impedance with rail to determine the current. The Simulink model for train occupation is given in Fig. 5, where a constant is set as an indicator to control switch SW2. It is set as one if the rail is occupied by a train, and reset to zero if there is no train on the track.

![Fig. 5. Simulink model for train occupation](image)
3.4 Track circuit termination

Separation of carrier frequencies on the contiguous track circuits can be achieved either conventionally through the use of insulated joints (IJ) which break the rail electrical continuity, or through electrical separation joints (ESJ) which do not require discontinuity. To save space, only the Simulink model for ESJ is presented here.

Electrically, the ESJ consists of a track section limited at each end by an LC-type tuned circuits, known as Tuning Unit (TU). Each unit is tuned to have a maximum (or “pole”) terminal impedance at its carrier frequency to promote signal transmission, and have a minimum (or “zero”) terminal impedance at its adjacent track circuit frequency to prevent it from propagating beyond the ESJ extreme limits. The first tuning unit consists of an LC series circuit, and the second tuning unit consists of an LC series circuit mounted in parallel with another capacitor. \( R_1 \) and \( R_2 \) are internal resistance of the two TU inductors.

![Simulink model for ESJ](image_url)

Fig. 6. Simulink model for ESJ
An Air Track Transformer (non-saturable), called ATT, is located at the centre of two tuning units. It allows the connection, galvanic isolation and impedance adaptation, as well as re-equalisation of the traction return currents between rails. Since the length of running rail connecting the two Tuning Units is very short (say 29m), the ballast conductance and rail admittance inside the ESJ section are neglected to simply the mathematical model.

Fig. 6(a) shows the complete ESJ Simulink model, which includes TU1, ATT and TU2. Fig. 6(b) gives the details in TU2, and Fig. 6(c) gives the details of ATT combined with the running rail inside the ESJ section.

3.5 Receiver

The receiver is used to detect the presence of a train in the associated track section. The receiver must recognize both carrier signal frequency and carrier signal level. There are two receivers in the CSEE track circuits. The main receiver connected with the secondary winding of the ATT via a bandpass filter. The filter selects the signal which corresponds to its tune frequency and thus suppresses the other signals that may be present on the track. The input signal to this receiver is actually the secondary voltage of ATT, which is given as one output in Fig. 6(a). The other receiver is called Intermediate Receiver, or PPD (Pin Point Detector). The input signal for this receiver is the rail current, which can be easily derived from the running rail at the site of PPD installation.

4 Simulator

4.1 Matlab/Simulink based simulator

From the Simulink models presented above, a Matlab/Simulink based simulator for track circuit can be constructed, as shown in Fig.7. The parameters used in this simulator are measured in the field, as described below.

![Fig. 7 A simulator for track circuit](image)

4.2 Parameters

A Phillips PM6304 Programmable Automatic RCL meter was used to measure the parameters of a 512m section of 1067mm gauge, 60kg/m rail, on concrete.
sleepers and newly ballasted track between two sets of insulated joints. All track leads were disconnected during the test. The ballast conductance and rail admittance were determined from the open circuit test, while the rail resistance and inductance were determined from the short circuit test. The results for running parameters are given in Table 1. A number of Tuning Units (TU) and ATT in the CSEE track circuit were also measured with the RLC meter, as shown in Table 2. The measured turn ratio of ATT is 4.

Table 1. Electrical Parameters of the Running Rail

<table>
<thead>
<tr>
<th>R_{Rail}</th>
<th>L_{Rail}</th>
<th>C_{Rail}</th>
<th>G_{Ballast}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.976mΩ/m</td>
<td>1.321μH/m</td>
<td>257pF/m</td>
<td>6.67×10^{-7}S/m</td>
</tr>
</tbody>
</table>

Table 2. Tuning Unit & Air Track Transformer impedance

<table>
<thead>
<tr>
<th>R (mΩ)</th>
<th>L (μH)</th>
<th>C_{1}/C_{2} (μF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1700Hz TU</td>
<td>77.6</td>
<td>34.5</td>
</tr>
<tr>
<td>2000Hz TU</td>
<td>53.7</td>
<td>40.5</td>
</tr>
<tr>
<td>2300Hz TU</td>
<td>41.6</td>
<td>88</td>
</tr>
<tr>
<td>2600Hz TU</td>
<td>36.4</td>
<td>95</td>
</tr>
<tr>
<td>ATT</td>
<td>22</td>
<td>32700</td>
</tr>
</tbody>
</table>

5 Results

5.1 Measurements

The signals in CSEE track circuit were measured in field with the Tektronix TDS 744A, as shown in Fig. 8, where M1 is the 2000Hz transmitter output, M2 is the 2600Hz transmitter output, and M3 is the 2000Hz PPD input.

Fig. 8 Measured transmitter and receiver signals
5.2 Transmitter output

To obtain 1Hz resolution spectrum, the simulation was processed for 1 second in real-time. For 5μs per step in simulation, this gives 200000 data points for FFT analysis. Fig. 9 shows the spectrum of transmitter output voltage at 11.3V peak (8.5V rms) with a basic carrier frequency of 2000±11Hz. This spectrum mainly consists of 2kHz and 2k±11Hz components. It can be seen that the simulation agrees with the measurement.

![Fig. 9 Transmitter output signal](image)

5.3 Receiver input

The receiver used here is 566m away from the transmitter. Fig. 10 shows its input voltage spectrum under transmitter output of Fig. 9. It also shows a good agreement between simulation and measurement.

![Fig. 10 Receiver input signal](image)

6 Conclusions

A simulator of the track circuit for urban/suburban transit system has been constructed with Matlab/Simulink. By means of this simulator, the carrier signal at every sub-system can be observed on the computer screen. It is a useful tool for demonstration and investigation for track circuit operation, as well as the optimum design of track circuit parameters. The major advantage of this simulator is to observe the transient process of the track circuit caused by
any parameter variations during simulation. There is a good agreement between measurement and simulation.

7 Acknowledgment

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8 References